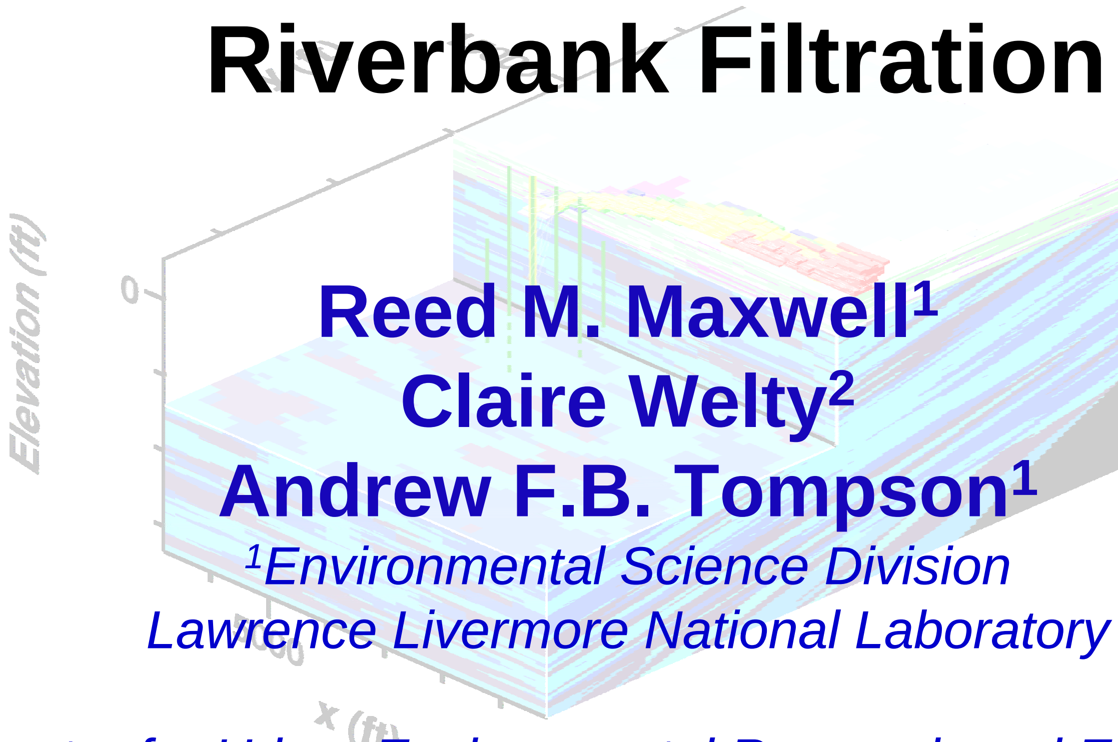
Streamline-Based Simulation of *Cryptosporidium* Transport in Riverbank Filtration



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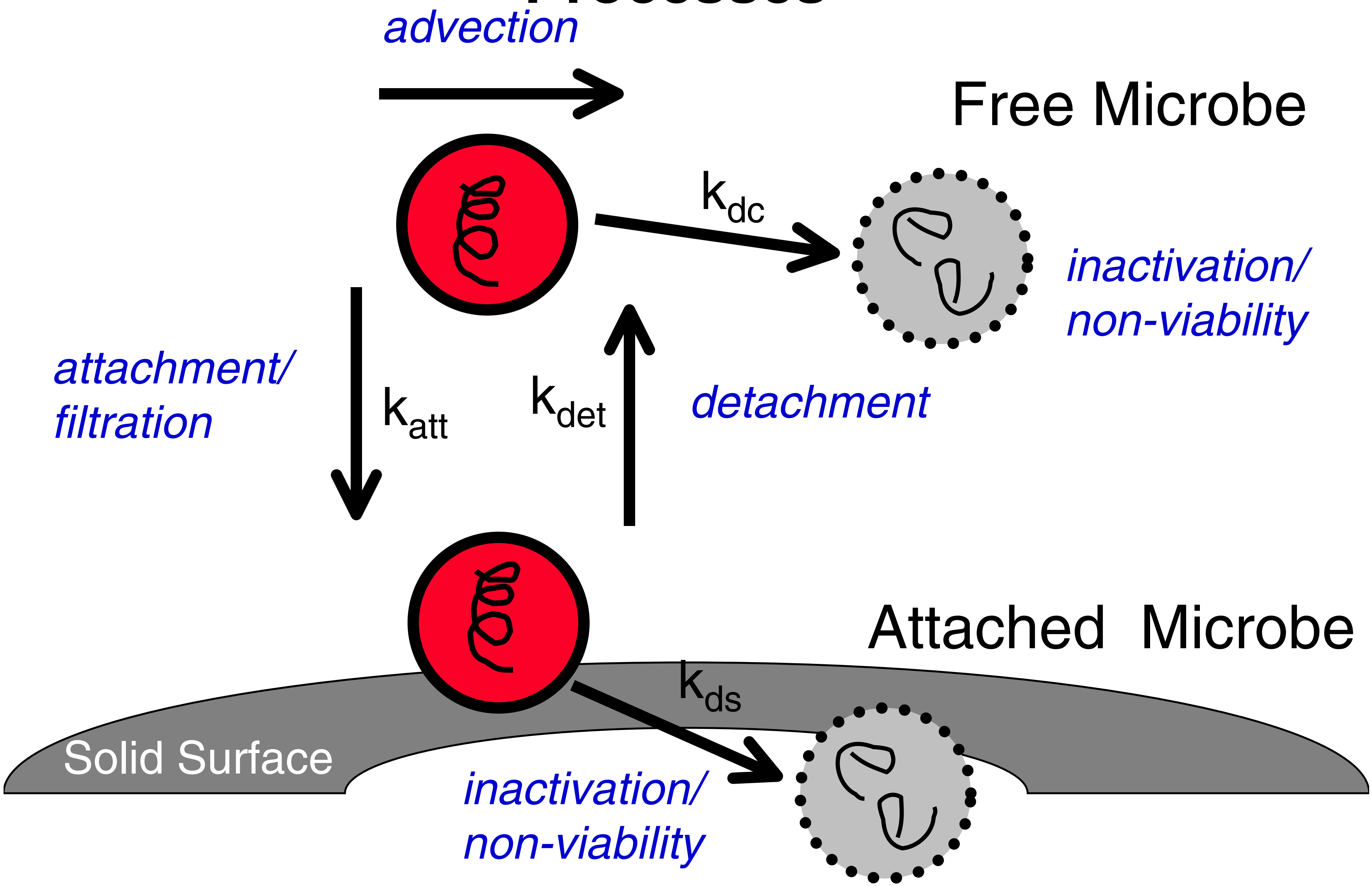
Objectives

- To evaluate the influence of geologic heterogeneity on field-scale microbial transport
- To incorporate any pattern of heterogeneity at any scale
- To investigate microbial transport in a simulated realistic heterogeneous setting
- To understand differences between heterogeneous microbial transport and heterogeneous solute transport
- To provide information about effectiveness of microbial filtration in a realistic setting

General Pathogen Transport Processes



Governing local-scale equations

Free Microbes (C)

$$\frac{\partial C}{\partial t} = -\underbrace{\frac{\partial}{\partial x_i}(v_i C)}_{\text{advection}} + \underbrace{\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j} \right)}_{\text{dispersion}} - \underbrace{k_{dc} C}_{\text{inactivation}} - \underbrace{k_{att} C}_{\text{attachment}} + \underbrace{k_{det}\frac{\rho_b}{\rho\theta} S}_{\text{detachment}}$$

Attached Microbes (S)

$$\frac{\rho_b}{\rho\theta}\frac{\partial S}{\partial t} = -\underbrace{k_{ds}\frac{\rho_b}{\rho\theta} S}_{\text{inactivation}} + \underbrace{k_{att} C}_{\text{attachment}} - \underbrace{k_{det}\frac{\rho_b}{\rho\theta} S}_{\text{detachment}}$$

$$k_{att} = \left[\frac{3}{2}\frac{(1-\theta)}{d}\alpha_c \eta \right] v_i$$

Colloid Filtration

(Rajagopalan and Tien, 1976; Martin et al, 1996; Logan et al., 1995)

Spatial Variability of Hydraulic Conductivity (K)

8 LEBLANC ET AL.: CAPE COD TRACER TEST, 1

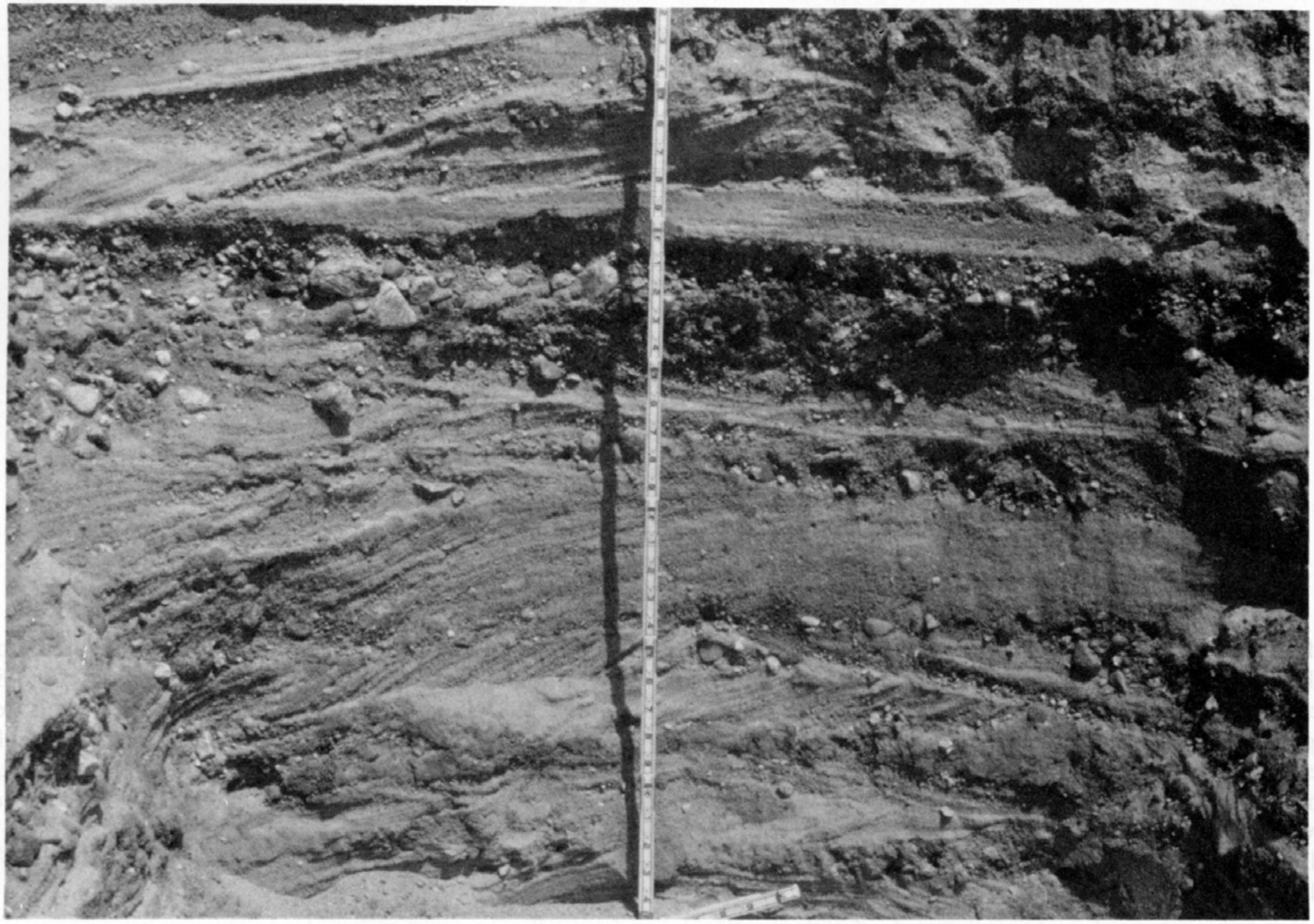
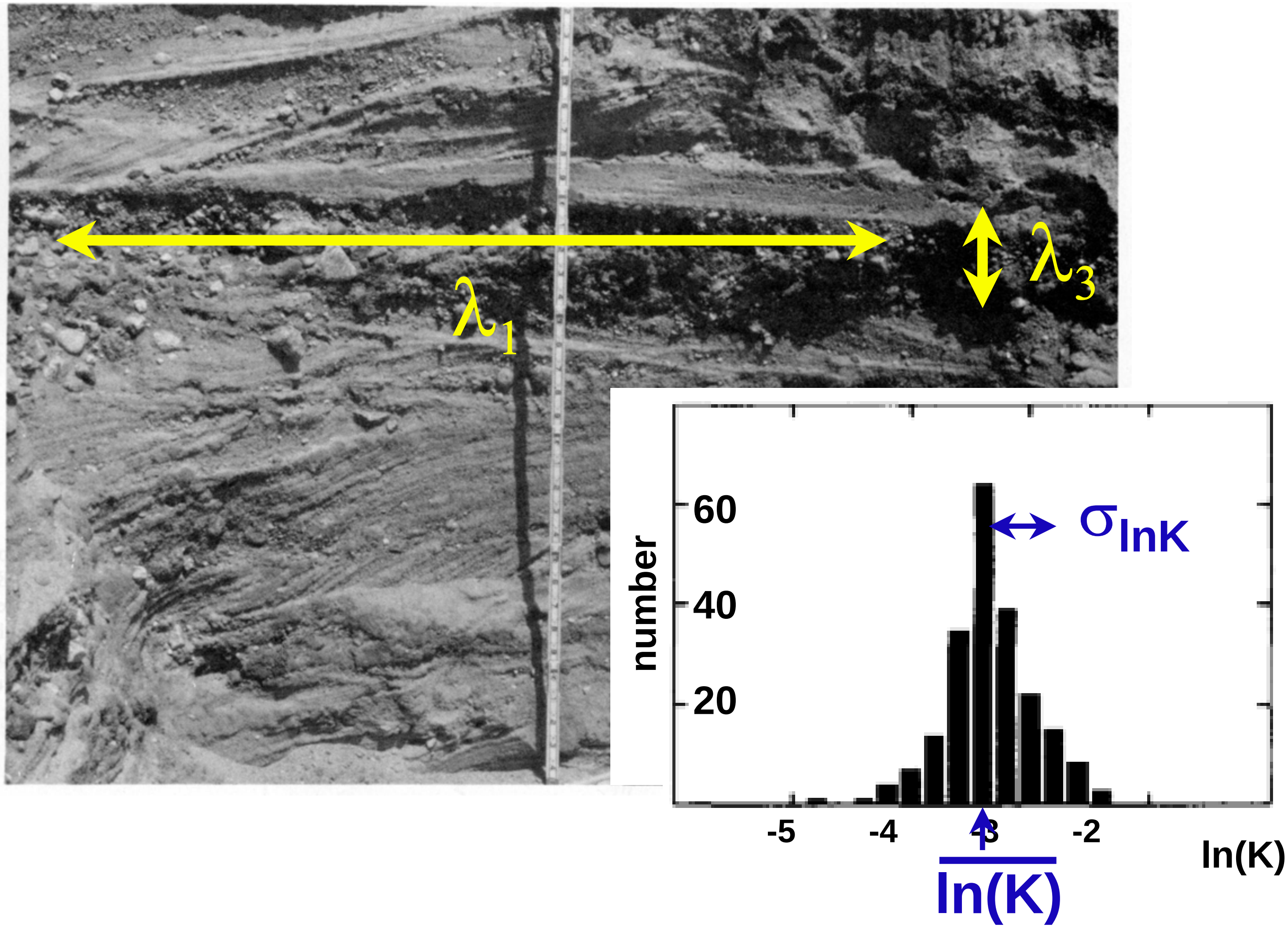


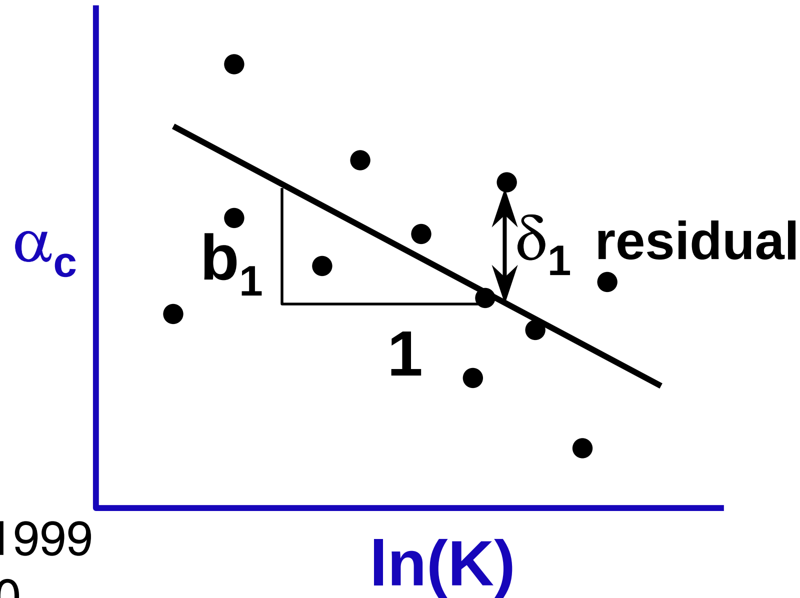
Fig. 3. Fresh exposure of sand and gravel outwash in test pit at tracer test site. Exposure in unsaturated zone about 5 m above water table. Height of section about 1 m. Location of test pit shown in Figure 4.

Statistical Characterization of Heterogeneity



Correlation of Colloid Parameters with Soil Type

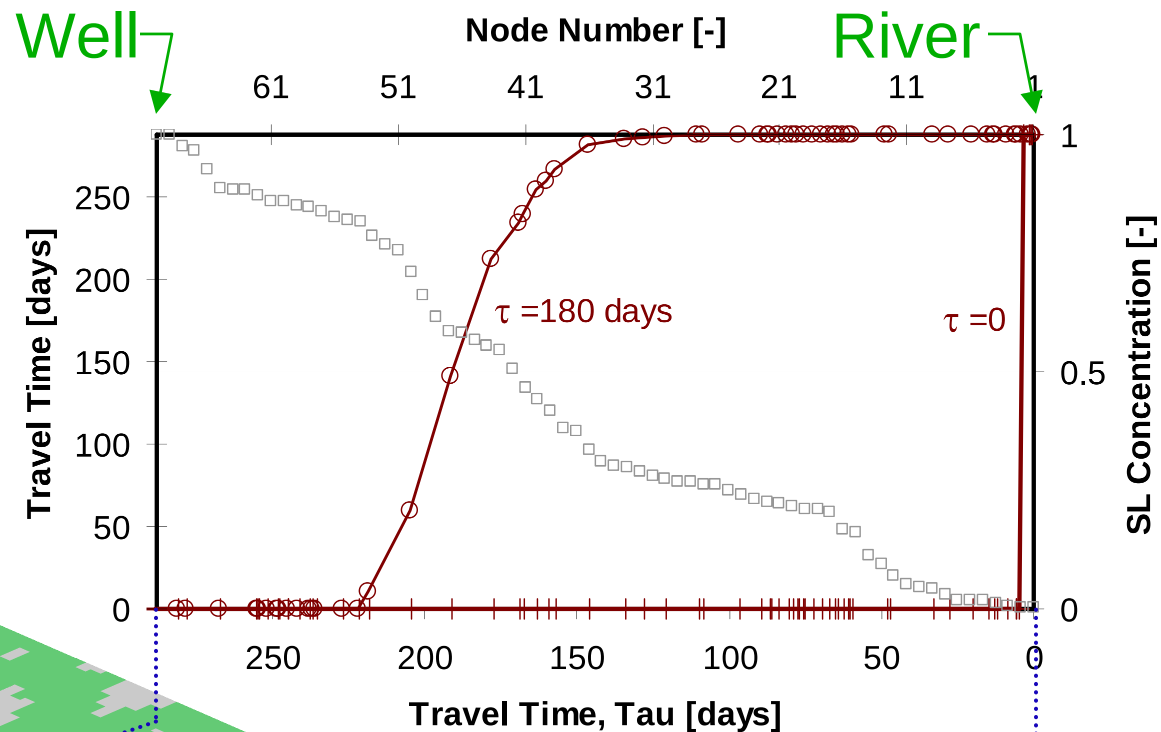
$$\alpha_c = a_1 + b_1 \ln K + \delta_1$$
$$\eta = f(\ln K, v_i)$$

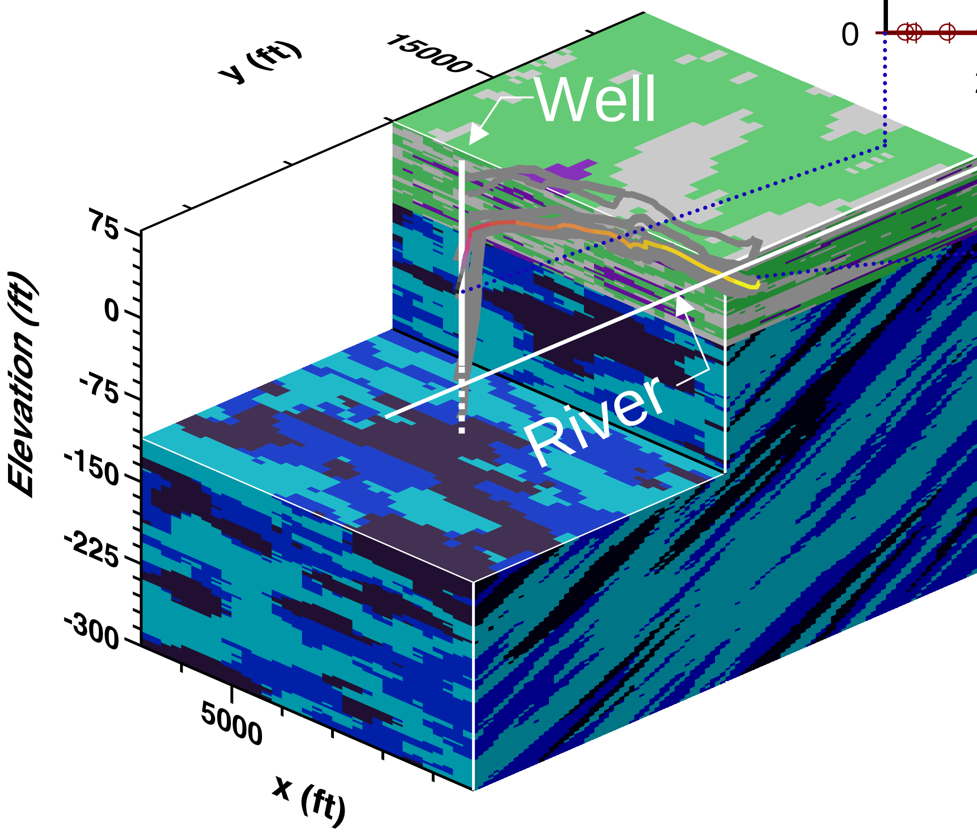


Correlations explored:

- •Rehmann, Welty and Harvey, *WRR,* **35**(7), 1999
- •Ren, Packman and Welty, *WRR,* **36**(9), 2000
- •Blanc and Nasser, *Water Sci &Tech*, **33**,1996
- •Harter and Wagner, *ES&T*, **34**, 2000

Streamline Modeling Approach





- •Streamlines are mapped and used to determine origin, travel time, travel pathway and flux of water entering a well screen
- •Forward colloid transport simulated along each streamline using finite-difference 1-D grid: advection terms solved explicitly via high-order TVD algorithm, attach/detachment terms solved implicitly
- •Concentrations are mapped from each 1-D streamlines onto the 3-D grid
- •Breakthrough curves at the well are flux-averaged across all streamlines

Orange County Case Study

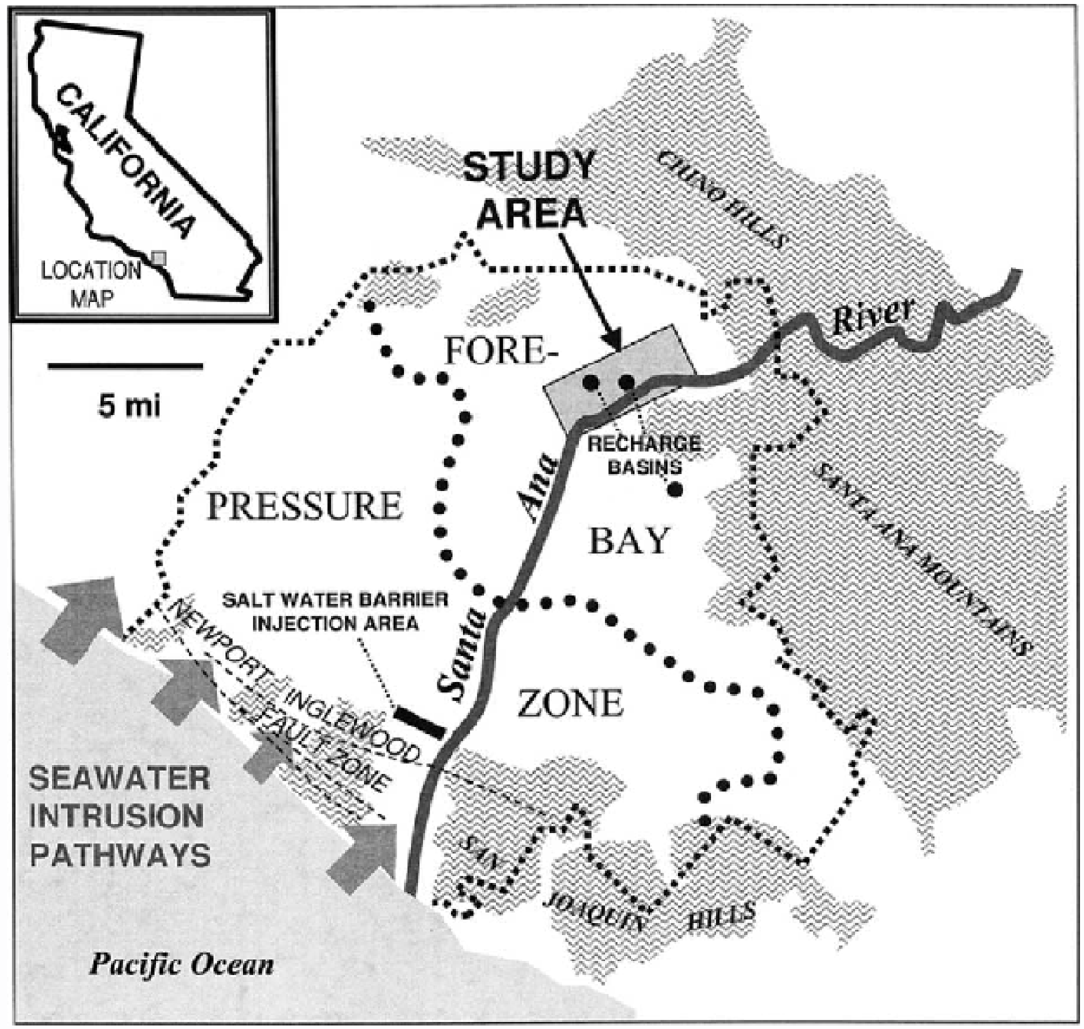
- Domestic supply for over 2 million residents
- Seek increased reliability
  - augment uncertain imported supplies
  - hedge against growth and increased demand
  - protection from earthquake interruption of surface deliveries
- Now:

  Active infiltration of Santa Ana River and imported water in Forebay recharge basins (equals 3/4 of annual extraction)
- Future:

  Supplemental recharge provided from recycled (waste) water

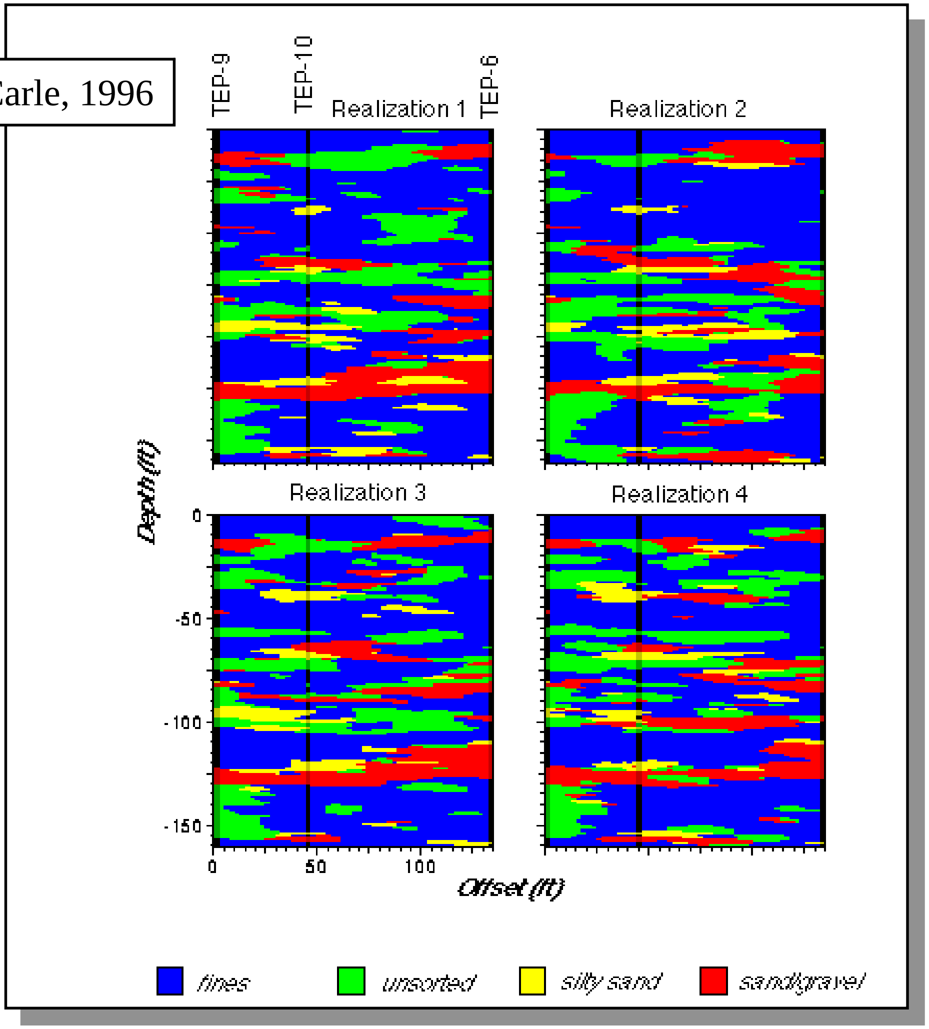
Primary regulatory concerns focused on water quality implications

- Water Quality Issues
  - longevity of microbiological elements in subsurface
  - increase of TDS from cyclic recharge
  - impacts of other organic contaminants
- Management Balances
  - tertiary treatment/disinfection
  - wetlands development
  - groundwater impacts/natural attenuation
  - emerging regulatory framework



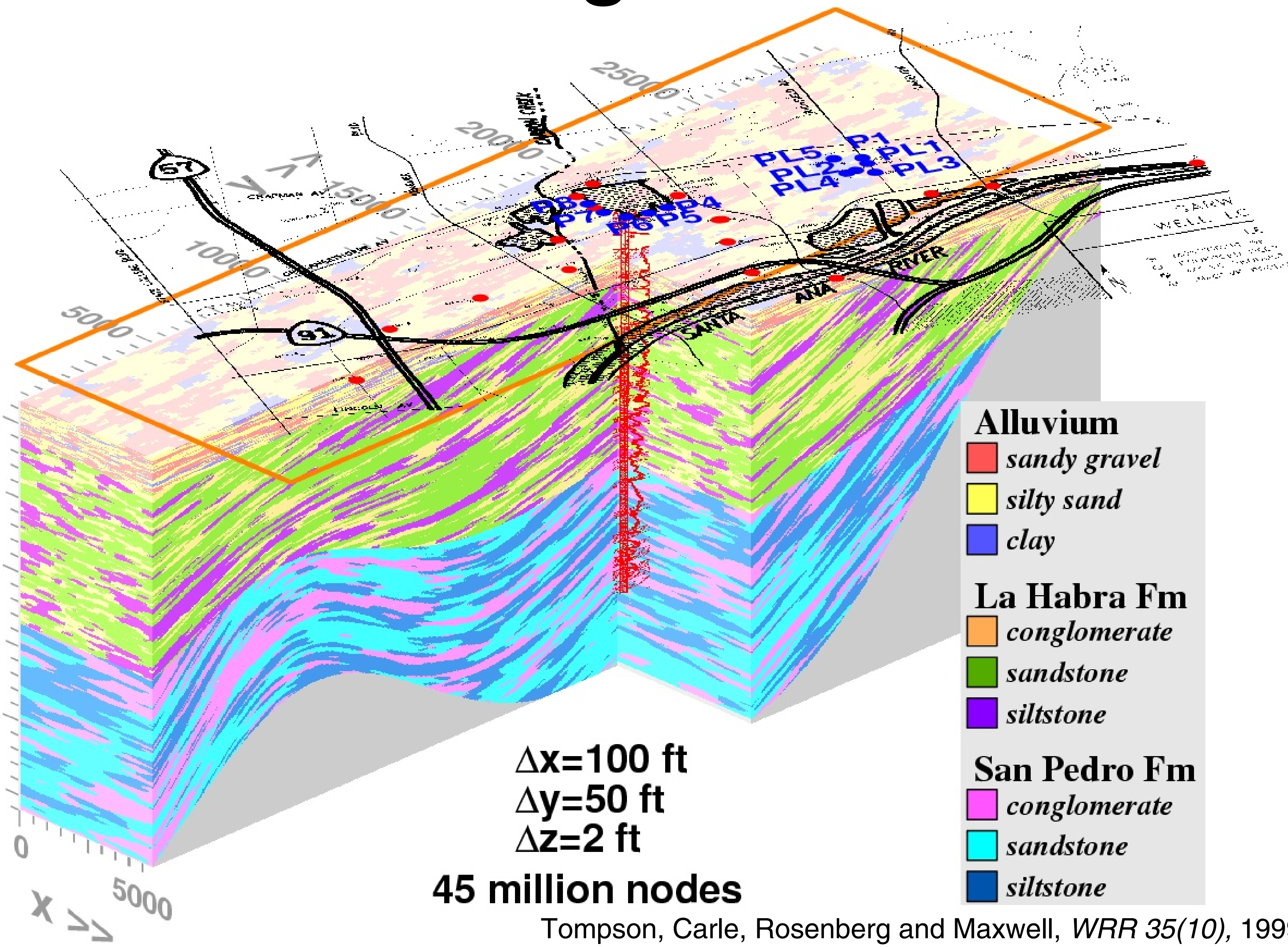
Correlated lithology indicator functions generate conditioned realizations of material categories

Carle, 1996



- Discrete representation
- Honors borehole lithologies
- Assume lithology categories correlate to permeability
- Representation of geologic structure is more realistic
  – less bias toward high permeability values
  – recreate measured transitional probabilities between facies
  – recreate volumetric abundance of individual categories
  – recreate representative length scales of individual categories
- Generate nonunique, equally probable “realizations”

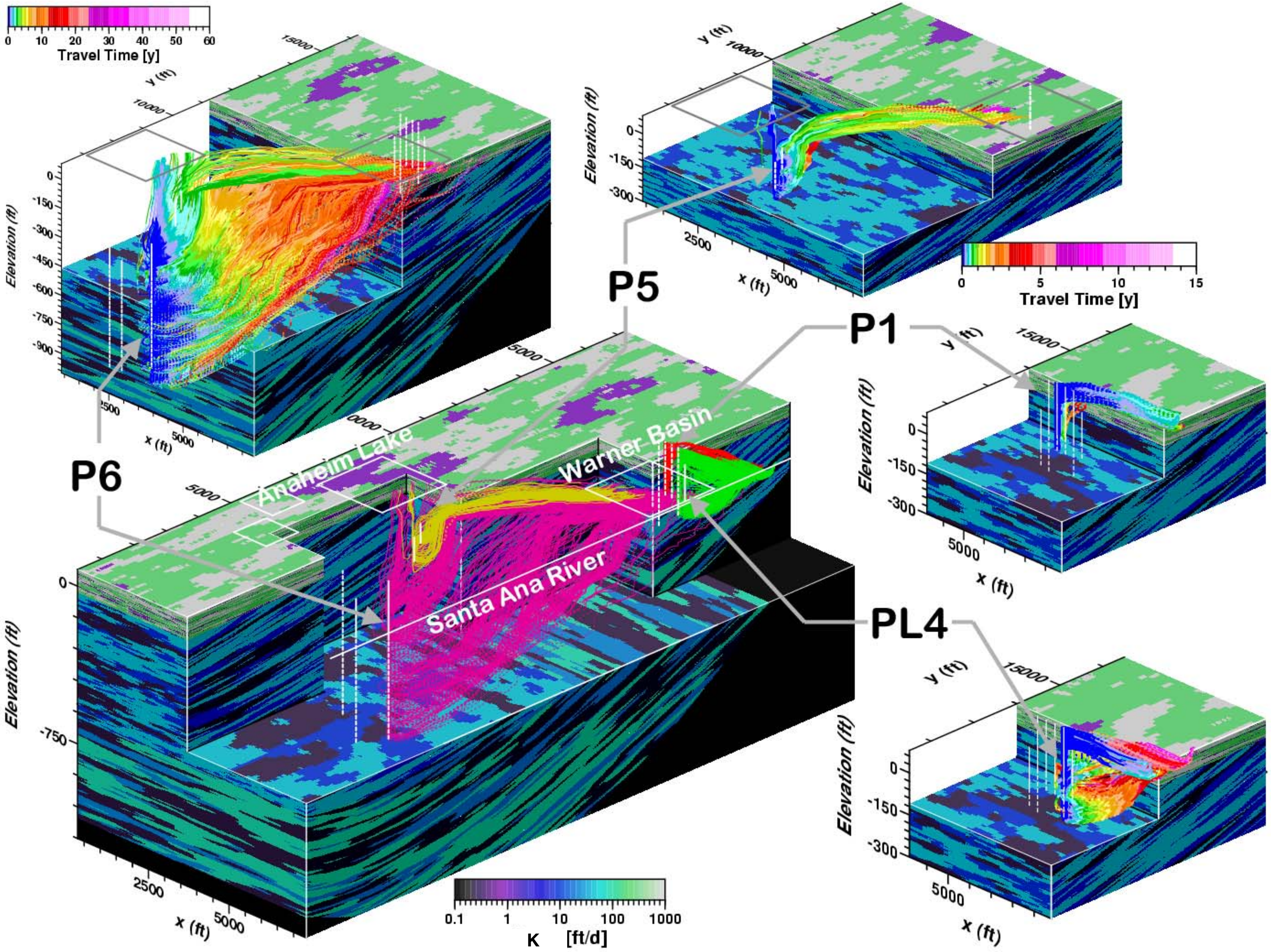
3D Geologic Model



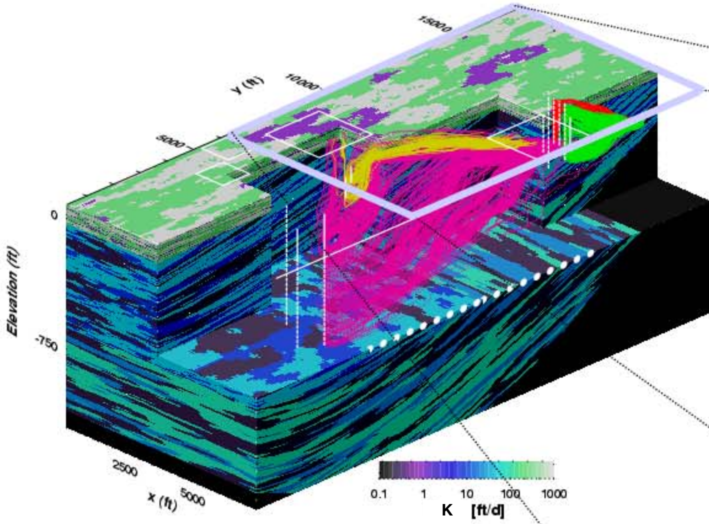
$\Delta x = 100$ ft
$\Delta y = 50$ ft
$\Delta z = 2$ ft
45 million nodes

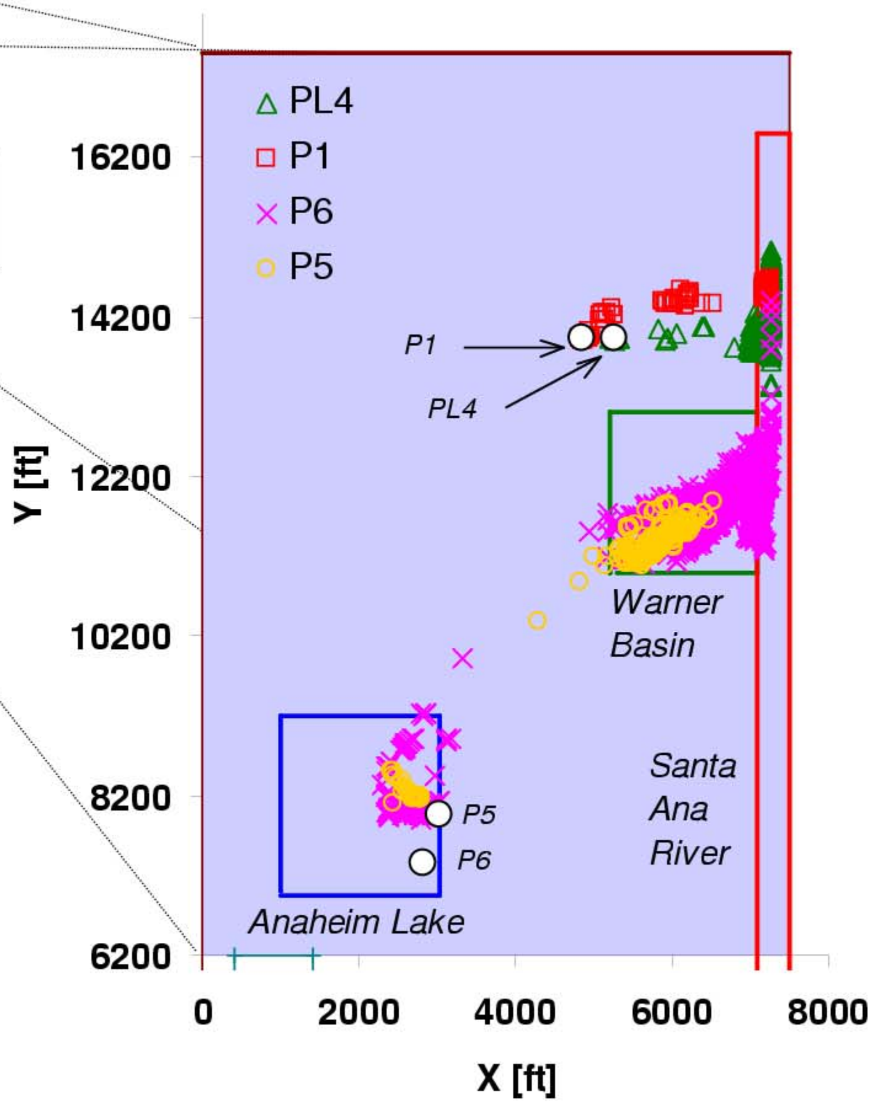
Tompson, Carle, Rosenberg and Maxwell, *WRR 35(10),* 1999.

Reverse Streamline Traces



Recharge Well Locations

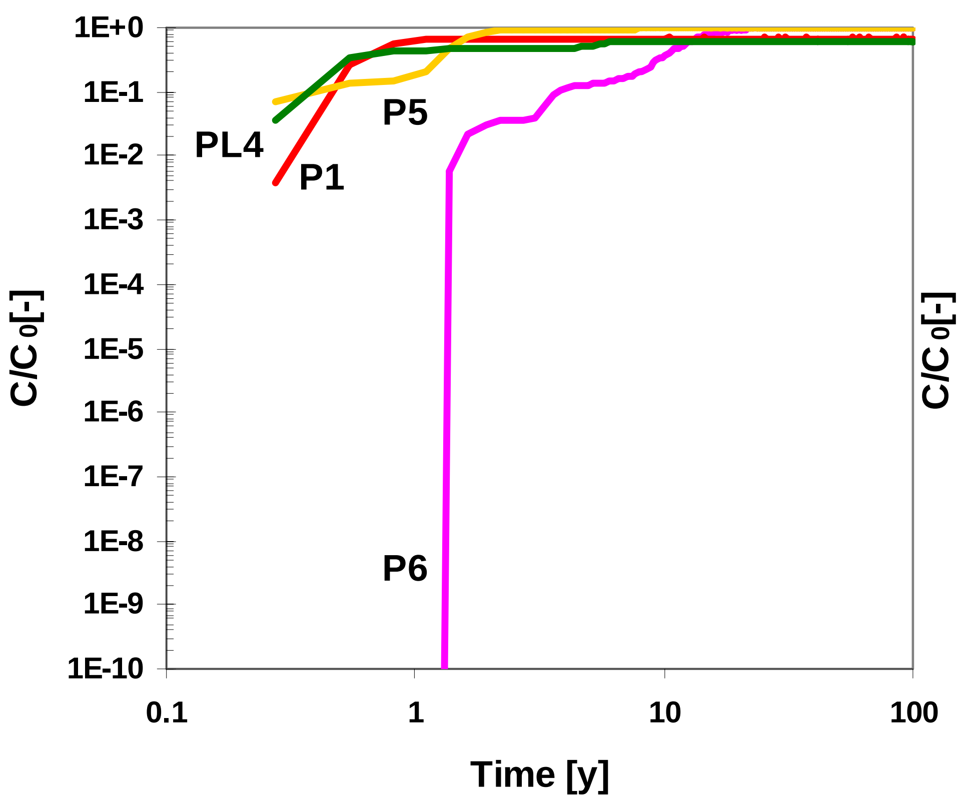




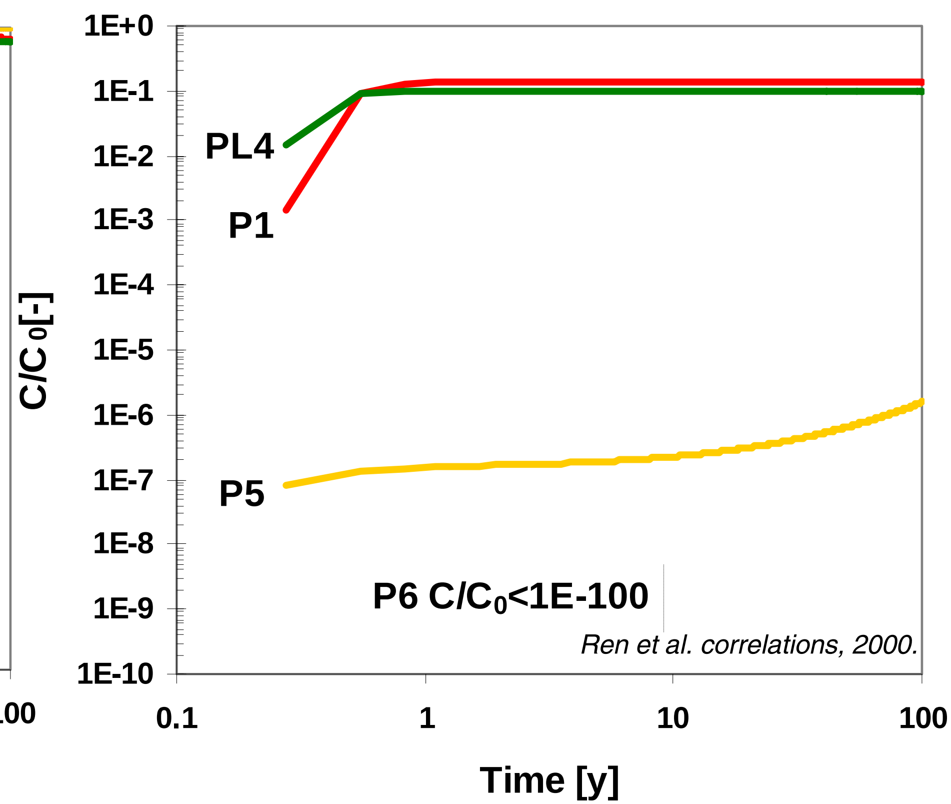
Predicted Mean
Water Age:
P5: 1.4 yr
P6: 11.9 yr
P1: 0.41 yr
PL4: 0.89 yr

Comparison among wells

Tracer Transport

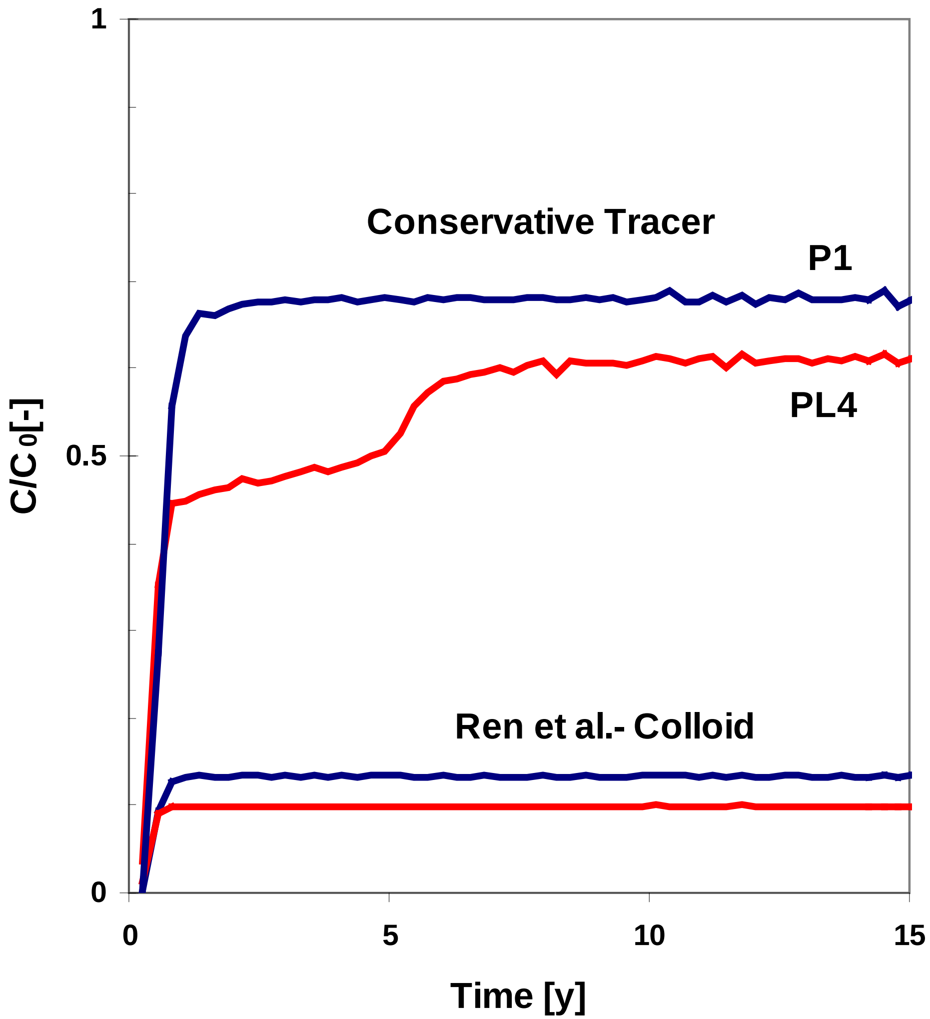


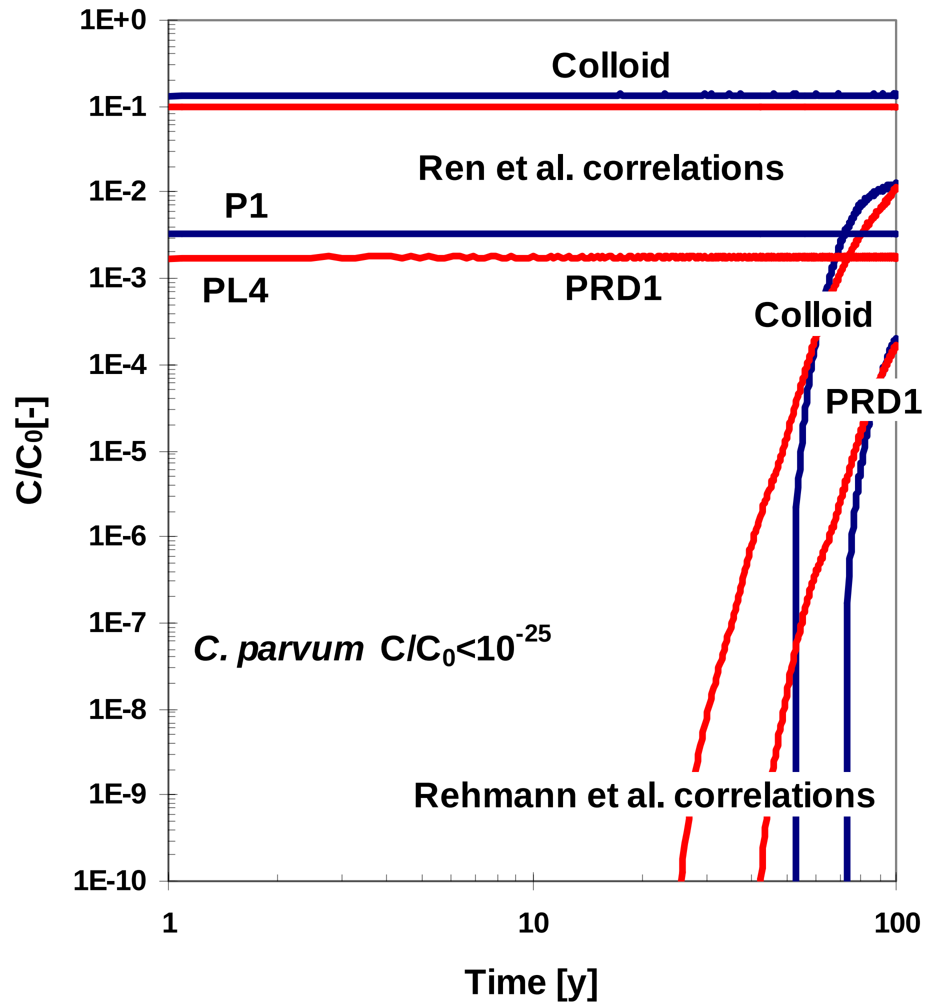
Colloid Transport



Colloid breakthrough very different *in character* than tracer breakthrough

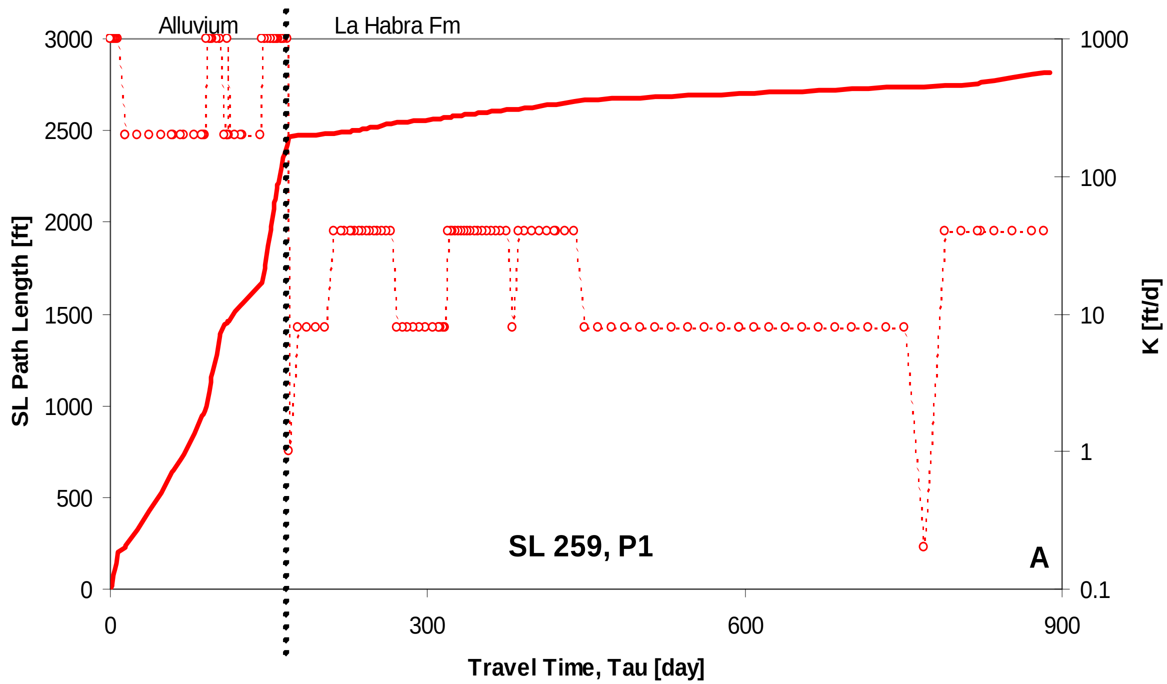
Breakthrough curves for tracer, colloids, PRD1, *C.parvum*- Wells P1, PL4

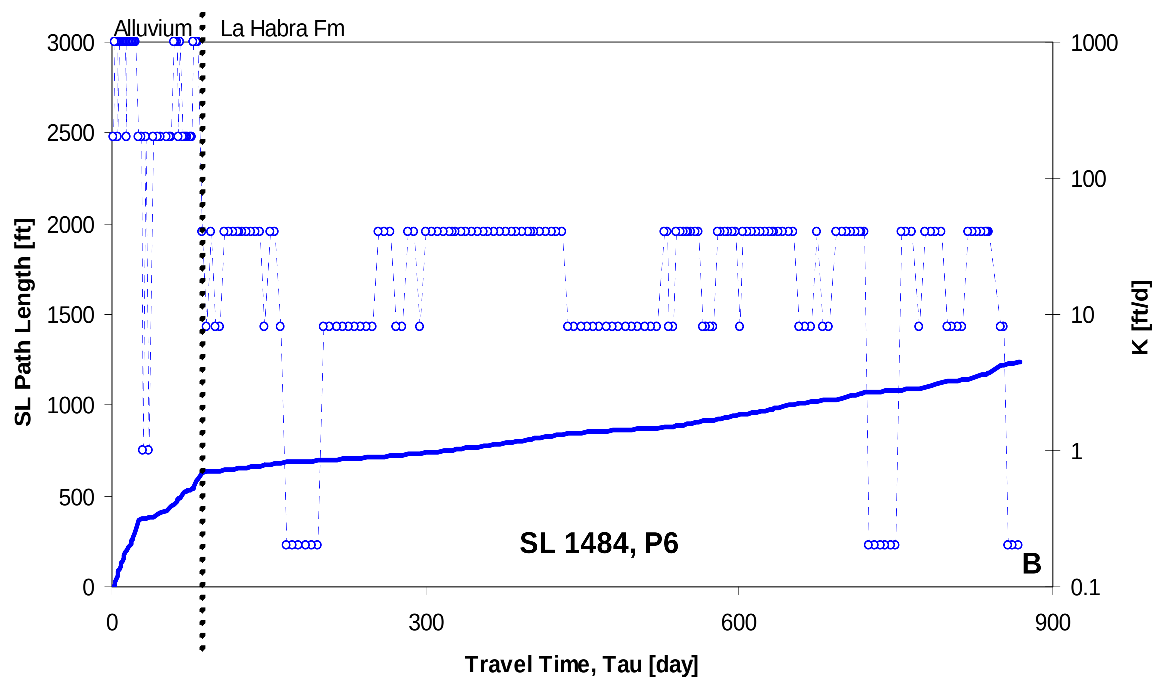




Comparing Two Streamlines

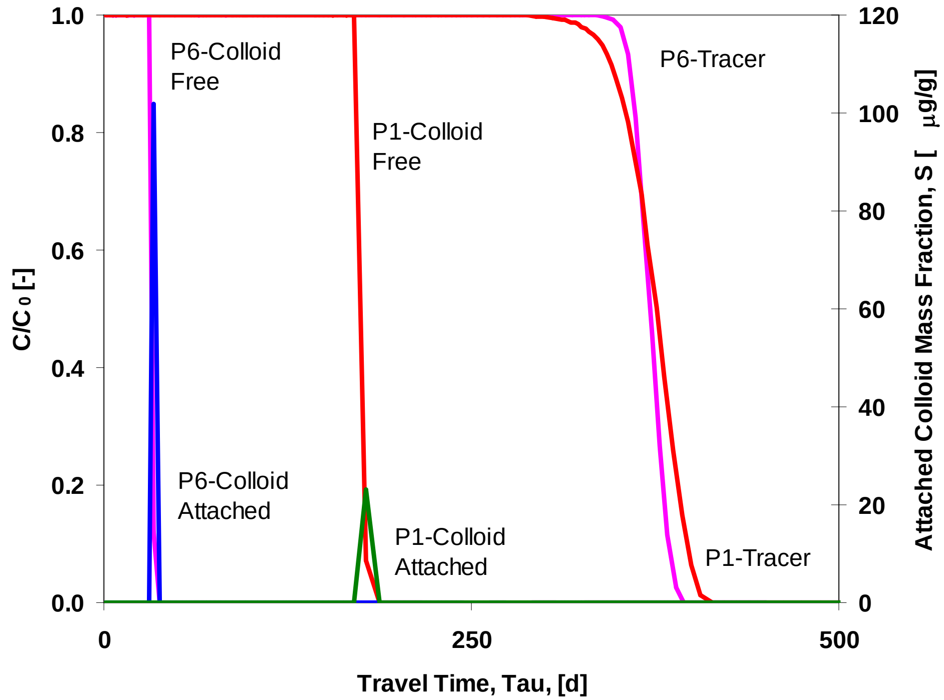
- Same travel time, much different travel distances
- Different amount of time spent in different formations

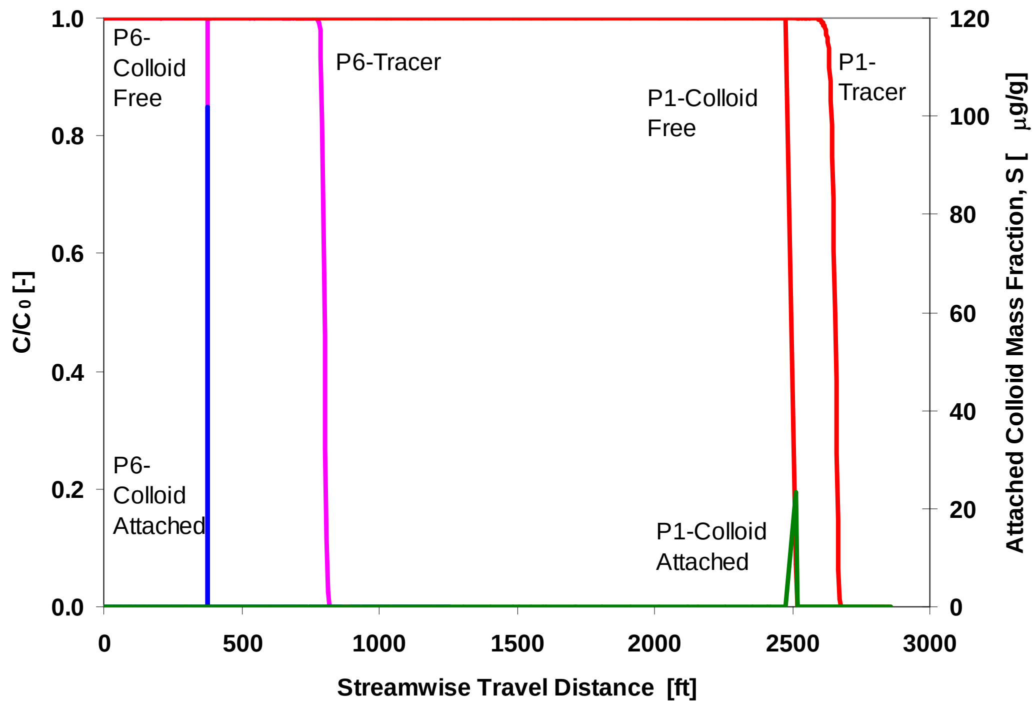




Comparing Two Streamlines, Transport

- Same travel time, much different travel distances
- Different time/location of filtration





Summary

- 1D streamline approach is presented for carrying out microbial transport simulations in a large, heterogeneous 3D domain
- In high-K layers, microbes may behave as a conservative tracer
- K variability significantly affects colloid filtration
- The postulated correlation between lnK and α_c is very sensitive to parameterization (slope)
- Shallow wells may be more vulnerable to microbial contamination than deeper wells (low-k unit)
- *C.parvum* was greatly filtered due to large particle diameter and filtration correlations

Maxwell, Welty and Tompson, *Advances in Water Resources* **26**(10):1075-1096, 2003

Future Work

- Better model for correlation of *C.parvum* parameters with hydraulic conductivity
- Integrated Microbial Risk Assessment Framework

Portions of this work were conducted under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory (LLNL) under contract W-7405-Eng-48.